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The X12/3B solar flare that occurred at heliographic coordinates N33, W69 in NOAA region 6659 on 15 June 1991 commencing at 0810 UT was the source of a number of energetic phenomena. In addition to the intense X-ray and gamma-ray emission, and probable neutron emission; the flare phenomena also accelerated ions to relativistic energies. The long duration associated GLE observed at the earth was essentially isotropic during the maximum and decay phase of the event. The lack of observed flux anisotropy is probably due to the very disturbed interplanetary propagation conditions rather than solar source characteristics. The GLE maximum of 20 $\pm$ 4% occurred at about 0930 UT. A differential rigidity spectra having a slope of -6 reproduces the observed increases at neutron monitor energies, but this slope does not extrapolate to satellite measured fluxes below 100 MeV.

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THE RELATIVISTIC SOLAR PROTON EVENT OF 15 JUNE 1991

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ABSTRACT

The X12/3B solar flare that occurred at heliographic coordinates N33, W69 in NOAA region 6659 on 15 June 1991 commencing at 0810 UT was the source of a number of energetic phenomena. In addition to the intense X-ray and gamma-ray emission, and probable neutron emission; the flare phenomena also accelerated ions to relativistic energies. The long duration associated GLE observed at the earth was essentially isotropic during the maximum and decay phase of the event. The lack of observed flux anisotropy is probably due to the very disturbed interplanetary propagation conditions rather than solar source characteristics. The GLE maximum of 20 $\pm$ 4% occurred at about 0930 UT. A differential rigidity spectra having a slope of -6 reproduces the observed increases at neutron monitor energies, but this slope does not extrapolate to satellite measured fluxes below 100 MeV.

1. INTRODUCTION

The energy source for the 15 June 1991 relativistic solar cosmic ray ground-level enhancement (also called GLE) was the X12/3B solar flare at heliographic coordinates N33, W69 in NOAA region 6659. The H-alpha onset was 0810 UT. June 1991 was the month of an historic cosmic ray intensity minimum, and this time period is very disturbed with the occurrence of numerous powerful solar flares accompanied by multiple interplanetary shocks propagating through the heliosphere. Six sudden commencement geomagnetic storm onsets were recorded at the earth between 4 and 12 June. The historic cosmic ray intensity low occurred on 13 June 1991, two days before this GLE. These effects indicate that propagation conditions in the heliosphere were not quiescent. Also indicative of the non-quiescent propagation conditions were variations in the pre-event background at all stations exceeding those expected from Poisson statistics.

The world-wide network of neutron monitors recorded a small, approximately isotropic, long duration GLE on 15 June. At the time of the GLE maximum at about 0930 UT all high latitude neutron monitors recorded an increase of ~20 $\pm$4%. There was a very small flux amplitude anisotropy with stations viewing in the "forward" flux propagation direction such as Goose Bay, Canada recording an ~22 percent increase while stations viewing in the "reverse" flux propagation direction such as Tixie Bay, Russia observed an ~17 percent increase. An overall view of this long lasting, approximately isotropic GLE is presented in Figure 1.

The disturbed propagation conditions make it difficult to accurately determine the onset of this relatively slowly rising GLE. All high latitude stations definitely exceeded the prevent-event background variations after 0840 UT. The increase systematically equaled or exceeded the pre-event background variations

in the 0835-0840 UT time interval. We cannot identify a definite anisotropy in the onsets of the "forward viewing" stations as compared to "reverse viewing" stations. However, the IMP-8 spacecraft recorded a velocity-dispersive onset in its measurement range of 8 to 400 MeV. The onset for the highest energy measurement (190-400) MeV coincides in time with the neutron monitor onsets. The onsets in the 15-25 MeV range occurred after 0900 UT (T. Armstrong, private communication).

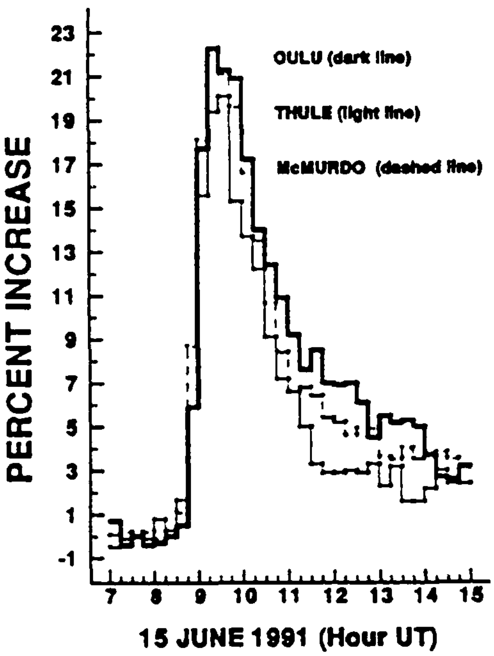

Figure 1. Illustration of the essentially isotropic GLE of 15 June 1991.

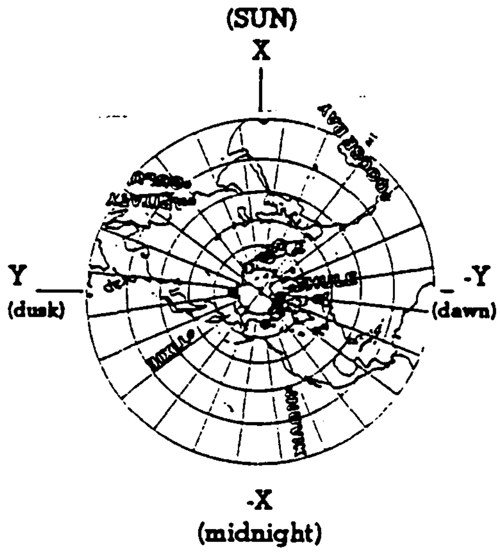

Figure 2. The orientation of the asymptotic cones of acceptance of selected high latitude neutron monitors to the IMF direction and the sun-earth line. At the time of the 0930 UT GLE maximum, the subsolar point was at 23° N latitude, 37.5° E longitude.

Charged particles of a specified energy arriving at a detector in a specific direction can be "mapped" to a unique direction in space (McCracken, 1962). The asymptotic direction of approach (Gall et al., 1982) defines an allowed particle's direction in space prior to its interaction with the earth's magnetic field. From the "geomagnetic optics" of high latitude neutron monitors, we can determine the orientation of the asymptotic cone of acceptance to the interplanetary magnetic field direction and estimate the flux arriving at each station. We define pitch angle zero as the direction of the IMF. At 09 hours UT the observed IMF was at GSE latitude -23° and GSE longitude 145°. Therefore the probable viewing direction into the solar proton flow was at GSE longitude of -35°. Figure 2 illustrates the orientation of the asymptotic viewing directions of selected high latitude neutron monitors with respect to the probable IMF direction and the sun-earth line.

There are direct interplanetary magnetic field (IMF) measurements by earth-orbiting spacecraft for 15 June 1991 until 09 UT. Then there is a four-hour data gap, one hour of IMF data at 14 UT; a one-hour data gap and then IMF data from 16 to 20 UT. Since there does not appear to be large variations in the IMF direction we may assume the IMF direction was relatively stable during the data gaps.

The geomagnetic field had been severely disturbed, and was undergoing a slow recovery from a major geomagnetic storm. At the GLE onset the Dst was -41 nT and was slowly recovering the remainder of the day.

2. DETERMINATION OF THE HIGH ENERGY SOLAR PARTICLE SPECTRA FROM THE ANALYSIS OF NEUTRON MONITOR DATA

We have used our standard technique for the analysis of GLEs (Shea and Smart, 1982) to determine the spectral characteristics and flux anisotropy of the 15 June event. The method is designed to reproduce the increase observed by the individual neutron monitors around the world. This can be done by numerical analysis of the solar particle spectrum and flux anisotropy directed along the interplanetary magnetic field, through the asymptotic cone of acceptance for each station (Gall et al., 1982) and then through the neutron monitor yield function (Lockwood et al., 1974). For this analysis we have used the Debrunner et al. (1982) neutron monitor yield functions to successfully reproduce the observed increases at each neutron monitor. We model the increase utilizing the functional form,

$$I = \sum_{P_0}^{\infty} J(\alpha,P)\, S(P)\, G(\alpha)\, dP \qquad (1)$$

where I is the increase at the neutron monitor, P_0 is the cutoff rigidity, $J(\alpha,P)$ is the differential flux in the interplanetary medium at pitch angle α and rigidity P that is allowed through the asymptotic cone of acceptance, S(P) is the neutron monitor specific yield, and $G(\alpha)$ is the anisotropic pitch angle distribution. Figure 3 illustrates the pitch angle distribution required to generate the small particle anisotropy at the GLE maximum. This form is similar to the exponential form derived by Beeck and Wibberenz (1986).

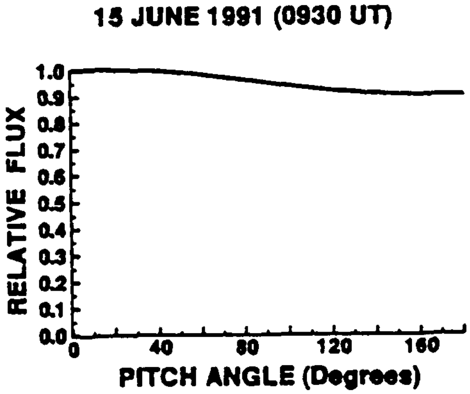

Figure 3. Solar particle flux pitch angle distribution necessary to produce the observe variation in the high latitude neutron monitors at the 0930 UT maximum of the 15 June 1991 GLE.

A power law in rigidity having a slope of -6.0 yields a satisfactory fit to the increases observed by the various neutron monitors as a function of latitude. For this event there were measurable increases for stations at a quiescent geomagnetic cutoff of ~6 GV. In our analysis method, if we assume an omnidirectional flux, a differential power law in rigidity with a slope of -6.0 generates the observed 0.7% increase at Rome and the sea level equivalent for the 12-NM-64 neutron monitor at Alma Ata, Kazakhstan. When we include the slight anisotropy we find that the spectrum cannot be harder than -5.5 or we would predict a larger increase than was observed at these stations. Since this was a long duration GLE we can also determine the spectra at other times. We derive a differential rigidity spectrum which gives the flux, J, in units of $(\mathrm{cm}^2\text{-s-ster-GV})^{-1}$. We find the high energy solar cosmic ray differential rigidity spectrum to be

$$J = 19.7\, P^{-6.0} \text{ at 0930 UT, and } J = 12.5\, P^{-6.0} \text{ at 1030 UT.}$$

In Figure 4 we have integrated the spectrum derived from the analysis of the neutron monitor data and extended this spectrum to the lower energies measured by the earth-orbiting spacecraft GOES-6 and GOES-7 (Courtesy of H. Sauer, private communication). In addition to the corrected integral flux at 30, 50, 60 and 100 MeV, there is a higher energy particle detector on the GOES-6 spacecraft from which the integral flux above 355, 433 and 505 MeV can be obtained. We have plotted these data in Figure 4 for comparison. Inspection of this figure shows that the power law in rigidity with a slope of -6.0 does not

smoothly extrapolate to the spacecraft energies below 100 MeV. Further inspection of this Figure suggests that a "broken power law" type of spectra may be a better representation of the solar particle flux.

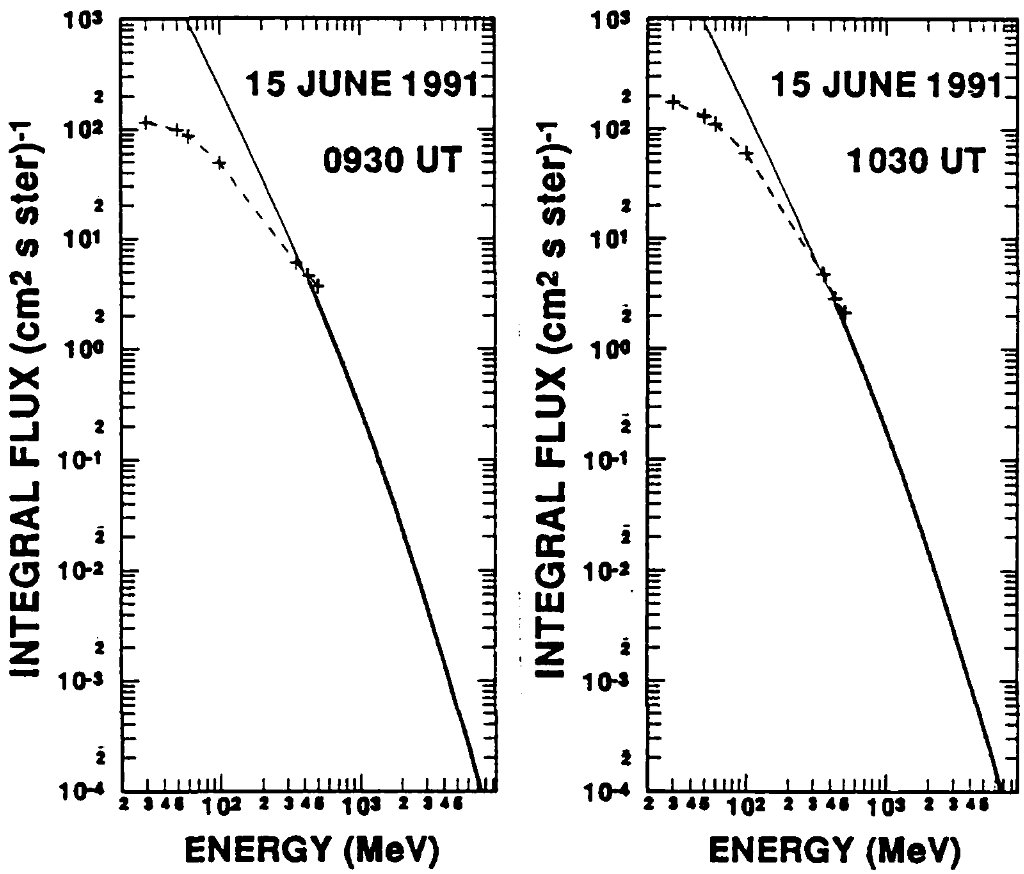

Figure 4. Spectra derived for the GLE of 15 June 1991 at 0930 UT (Left) and 1030 UT (right). The differential rigidity spectrum has been integrated and converted to an integral energy spectrum for comparison purposes. The heavy dark line indicates the spectrum derived from analysis of the neutron monitor data. The light line is this spectrum extended to the satellite measurement energies. The + symbol indicates the measured satellite integral flux.

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